Effects of land use conversion on selected physico-chemical properties of peat in the Leyte Sab-a Basin Peatland, Philippines

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SUMMARY

Tropical peatlands are unique wetland ecosystems which provide various ecosystem services such as carbon storage and nutrient cycling. However, they have been substantially altered and transformed by land use conversion. The present study investigated the effects of land use conversion on the physico-chemical properties of peat in the Leyte Sab-a Basin Peatland, a tropical peatland on Leyte Island, Philippines. Peat core samples (1 m long) were collected from peat swamp forest, grassland and cultivation areas. Samples were analysed for gravimetric water content, volumetric water content, dry bulk density, porosity, pH, organic matter, total nitrogen and total phosphorus. Notably, conversion of peat swamp forest to other land uses (grassland and cultivation) has resulted in changes in peat physical properties such as reduced water content and porosity, and increased bulk density. A reduction in peat water content can be a direct consequence of peatland drainage while an increase in peat bulk density with reduced porosity reflects compaction owing to the passage of agricultural equipment and peat decomposition. Land use conversion altered chemical properties characterised by reduced organic matter and nutrients (total nitrogen and total phosphorus) in grassland or cultivation, indicating peat decomposition and mineralisation. In addition, decrease in peat water content due to drainage and increase in bulk density can be accompanied by losses of organic matter and nutrients. Finally, changes in peat physico-chemical properties as a consequence of land use conversion serve as important indicators of peat soil degradation.

KEY WORDS: peat decomposition, peatland degradation, peat soil, peat swamp forest, tropical peatland

INTRODUCTION

Globally, peatlands are important but vulnerable resources. These ecosystems represent a significant carbon and energy reservoir and play major roles in water and biogeochemical cycles (Rezanezhad *et al*. 2016). A peatland is characterised by the accumulation of partially decomposed vegetation or organic material (i.e., peat), low pH, high groundwater level and low nutrient content (Miyamoto *et al*. 2009). Peat formation is favoured by low topographic relief, poor drainage, permanent waterlogging and high rainfall (Wösten *et al*. 2008, Page *et al*. 2010). The latter provide suitable conditions for slow decomposition of organic material and the accumulation of thick (often > 10 m) deposits of woody peat, particularly in tropical peatlands (Page *et al*. 2010).

Peatland soils store a large proportion of the global soil carbon pool, which might be lost via vertical (CO_2, CH_4) and lateral (waterborne carbon) pathways as a result of peatland degradation (Krüger *et al*. 2015, Tiemeyer *et al*. 2016, Glina *et al*. 2021). As a result of increasing population and global demands, tropical peatland may become important as arable land (Yonebayashi *et al*. 1994, Jaafar *et al*. 2020). The degradation of tropical peat usually starts when it is being drained and cleared to create open peatland to accommodate food crops, oil palm and industrial timber plantations. Other than the removal of vegetation, the conversion of peatland forest is usually accompanied by the construction of drainage canals that lower the water table to create a favourable medium for growth of crops (Anshari *et al*. 2010). Drainage causes irreversible lowering of the surface (subsidence) as a consequence of peat shrinkage and biological oxidation, with the latter resulting in a decrease of carbon stock (Hooijer *et al*. 2012).

The effects of peatland forest conversion are not limited to peat subsidence and carbon loss, but also include changes in the physical and chemical properties of peat. Land conversion results in changes in peat physical properties over time, through a combination of physical collapse of peat structure following drainage, and decomposition (Tonks *et al*. 2017). To a large extent, the state of peat decomposition determines properties such as hydraulic conductivity, water retention (Wösten *et al*.

2008), porosity and bulk density. For example, high bulk density is an indicator of peat degradation which may suggest peat oxidation (Krüger *et al*. 2015) and removal of lignified root biomass during ground preparation (Tonks *et al*. 2017). Likewise, continuous decomposition alters organic matter components and chemistry due to the rapid decrease in polysaccharide, tannin, hemicellulose, and cellulose contents (Yonebashi *et al*. 1994). Prior studies have shown that drainage and conversion of peatlands have resulted in the alteration of other peat chemical properties such as pH, C:N ratio and nitrogen forms - nitrate, nitrite and ammonium (Anshari *et al*. 2010, Frank *et al*. 2014, Könönen *et al*. 2015).

The Leyte Sab-a Basin Peatland (LSBP) has been deforested and drained for conversion to agricultural land, which has resulted in a decline of forest cover. A portion of the land was abandoned when it was found to be unproductive. Conversion of the peatland may have resulted in its degradation, characterised by alteration of the physico-chemical properties of the peat soil. At present, the effects of land use change in tropical peatlands are commonly discussed in terms of carbon emissions, with limited literature examining peat soil properties (Tonks *et al*. 2017). Indeed, to the best of the authors' knowledge, no previous studies of peatlands in the Phillipines have directly evaluated the effects of land use conversion on peat properties.

This study investigates how land use conversion alters the physical and chemical properties of peat. The objectives were to (a) determine the physico-chemical properties of peat soil in terms of gravimetric water content (GWC), volumetric water content (VWC), dry bulk density (DBD), porosity (P), pH, organic matter (OM), total nitrogen (TN) and total phosphorus (TP) across the different land use conversion classes (peat swamp forest, grassland and cultivation); (b) compare the physico-chemical properties of peat soil between land use conversion classes, depth classes and their interactions; and (c) evaluate the interrelationships between the physico-chemical properties of peat soil using regression analysis and principal component analysis (PCA).

METHODS

Study area

The LSBP has the second most significant peat deposit in the Philippines, next to the Agusan Marsh of Mindanao (Figure 1). It is a typical peat swamp forest area fed by water coming from all directions and various sources such as surface runoff, rivers and aquifers (ADB 2000) indicating that the LSBP is a minerotrophic type of tropical peatland (Page *et al*. 2010). It is an elongated basin with a centripetal drainage pattern (ADB 2000) and characteristically divided into four smaller peatland components though this study included only three adjacent peatlands. The peatland including the surrounding swamps has an area of 3,088 ha (APFP 2011), but recent estimates suggest that the peatland now has an area of about 2,108 ha (Garcia *et al*. in press). As observed, the peat in the LSBP is typically woody and herbaceous peat, and the maximum peat depth exceeds 10 m, especially in peat swamp forest areas.

The study area is located in the north-eastern portion of Leyte Island, covering the municipalities of Alangalang, Santa Fe and San Miguel. On its eastern flank, the LSBP is bordered by ultramafic outcrops known as the Tacloban Ophiolite Complex (TOC). The underlying sediments of the peatland are composed of alluvial deposits derived from ultramafic rocks and sedimentary sequences (Suerte *et al*. 2005). The peatland is drained by two river systems (Mainit and Bangon Rivers) along with artificial outlets created by blasting away a portion of the bordering hills.

During the 1970s, the Philippine government initiated a project funded by the National Food Authority and the Philippine Coconut Authority to drain the LSBP for agricultural development along with provisions of land ownership. In this project, about 1575 ha of previously forested LSBP was deforested, and canals and artificial water outlets were created for drainage purposes. However, these areas were abandoned after a few years of agricultural cultivation due to poor yield and are now dominated by extensive grasslands. This has resulted in a significant reduction of forest cover and probably degradation of the peatland. The remaining 1,288 hectares of managed peatland in the northern part of the basin consists of small remnant areas of peat swamp forest (APFP 2011).

The climate of the study area is characterised as equatorial rainforest-fully humid (Kottek *et al*. 2006). The study area has no pronounced rainy period and no dry season. The warmest month is April with a mean annual temperature of 27 ºC and pronounced wetness occurring in the months of November, December and January with an annual total precipitation of 2293 mm (Quiñones & Asio 2015, Marteleira 2019).

Study sites

Three land use conversion classes were identified in the peatland, namely peat swamp forest, grassland, and cultivation (Figure 1).

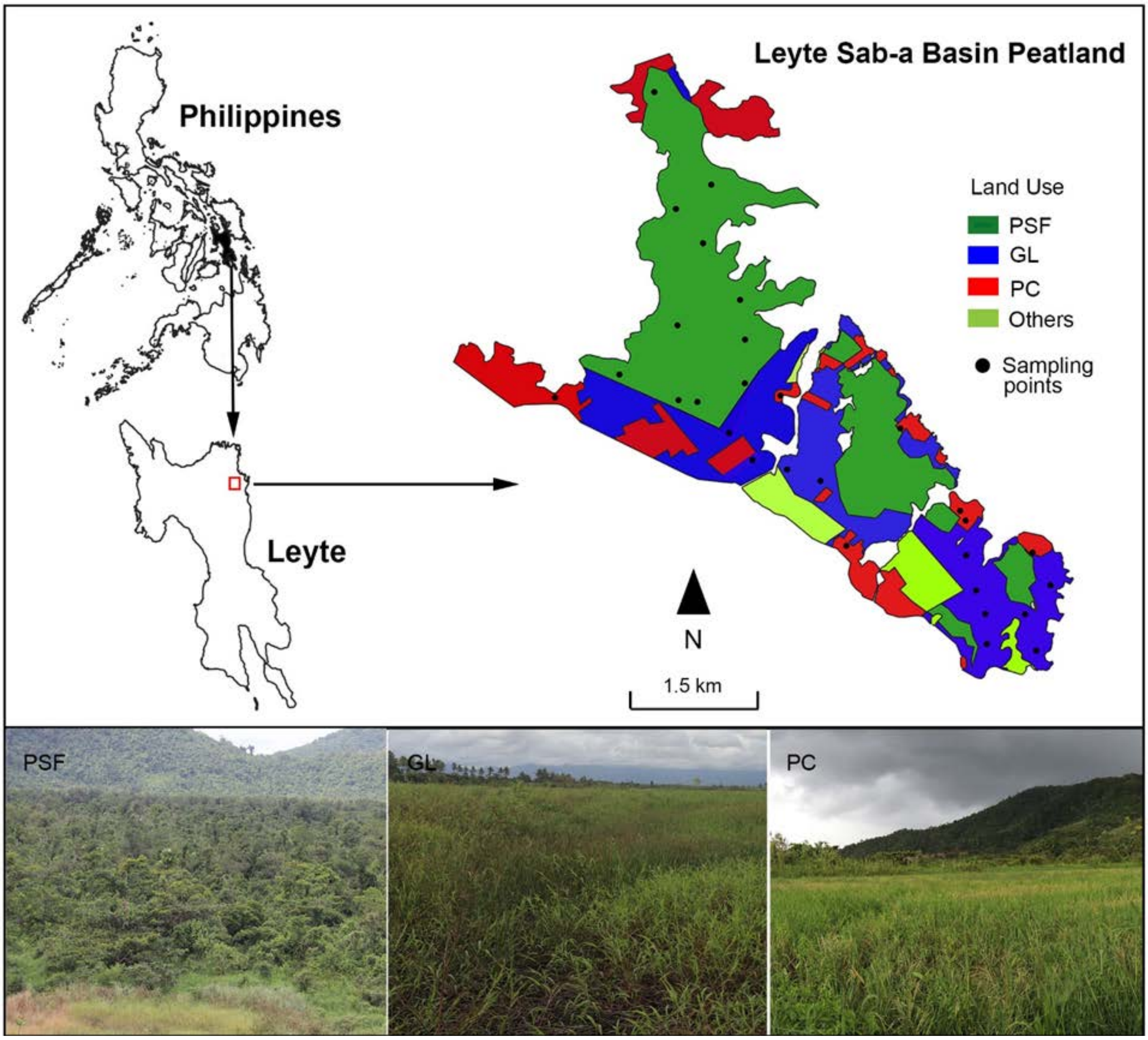

Figure 1. Map of the Leyte Sab-a Basin Peatland, locations of sampling points and land use. PSF=peat swamp forest, GL=grassland, PC=cultivation.

Peat swamp forest
The remaining forest areas are located at the northern part of the peatland and represent the original peat swamp forest. This forest is characterised by the presence of medium-sized trees with an average height of 6 m, often covered by very thick vines, and dominated by the tree species *Ilex cymosa* Hassk. The understorey layer is usually dominated by *Mapania sumatrana* (Miq.) Benth. and *Scleria scrobiculata* Nees & Meyen, plus a climbing fern species *Stenochlaena palustris* (NL Burm.) Bedd. Although these forest areas have no history of clear-cutting and draining, they have been subjected to some minor disturbances such as collection of wood for construction and fuel, fishing and wildlife poaching. They are important habitats for some wildlife species such as wild pigs and giant fruit bats. A few of the plots established were located in a patch of original forest surrounded by intermediate secondary forests.

Grassland
The grassland areas of the peatland are abandoned croplands or cultivated areas which are now dominated by sedges such as *S. scrobiculata* and *Fimbristylis globulosa* (Retz.) Kunth. with occasional trees of the species *Nauclea orientalis* (L.). The original land cover in these areas including the cultivated peatland was a dense peat swamp forest, however these were cleared and drained for rice production and other agricultural crops (ADB 2000). Constructed drainage canals approximately 1.00–3.00 m wide and 1.00–1.50 m deep can still be

observed but are already covered with vegetation which probably slows the process of draining. Some of these areas are being intentionally subjected to fire by people, in order to clear the vegetation for fishing purposes (but not for cultivation). In other cases fire spreads from nearby cultivation areas during the drier periods of the year. In addition, some of the grassland sites are grazed by water buffalo.

Cultivation

Peatlands with cultivation are situated in or surrounded by grassland and sedge areas along the periphery of the peatland, but only the portions with cultivation were included in our study. The cultivation areas considered were predominantly rice fields, although many patches of cultivated area were non-productive or showed unsuccessful attempts at cultivation. The dominant plant in these areas is a crop (*Oryza sativa* L.), accompanied by many other grass species. These rice fields are cultivated at least once a year and are fertilised with nitrogen, phosphorus and potassium usually in a form of urea or complete fertiliser. They are characterised by the presence of canals 1.30–1.70 m wide and 0.25–0.80 m deep, which were constructed to lower the water table and for irrigation purposes.

Field sampling and laboratory preparation

Eleven peat cores were extracted from peat swamp forest, eleven from grassland and seven from cultivation. In each case a core 100 cm in length was taken using a 60 mm diameter bi-partite gouge auger (Eijkelkamp, Netherlands). In the forest sites, cores were taken at least 1 m from the nearest tree because the presence of tree roots could prevent their extraction. Before the peat cores were extracted, sedges and grasses were removed using a machete. However, peat augering was discontinued whenever the auger encountered large living roots or hard undecomposed tree trunks buried in the peat, and on occasions when the sample was lost during lifting of the auger. Augering was then resumed approximately one metre from the previous hole. Each peat core was cut at 20 cm intervals resulting in a total of 145 samples. From each sample a 3 cm long subsample was separated for dry bulk density and water content determination, and the remainder was set aside for chemical analysis. The sample was then placed in a ziplock bag to avoid moisture loss.

At each sampling location, the water table level relative to the peat surface was measured to 0.50 cm accuracy using a ruler or metre stick. If positive it was measured from the peat surface to the water surface, and if negative it was measured from the peat surface down to the water table via the core sampler borehole. Peat depth was measured by inserting a single gouge auger until the mineral layer was reached, unless the peat depth exceeded 5 m when a bamboo or straight wooden pole was driven farther into the peat until it reached the mineral soil beneath. All sampling points were georeferenced by using a hand-held GPS (model eTrex). All the fieldwork took place during the period November 2020 to February 2021.

In the laboratory, peat samples were prepared for physical and chemical analysis. For chemical analysis the peat soil samples were air-dried for about two weeks, coarse debris such as roots was manually removed, the soil samples were homogenised and ground using a mortar and pestle, then the ground samples were sieved to pass through 0.425 mm mesh size to obtain a fine powder.

Soil analysis

Selected peat physical and chemical properties were determined to investigate the effects of land use conversion. Gravimetric water content (GWC), dry bulk density (DBD) and volumetric water content (VWC) were determined by oven drying the sample at 105 °C for 24 hours. Porosity (P) was derived from the DBD values and the most commonly used average particle density (PD) for peat of 1.40 g cm^{-3} (Rowell 1994, Tonks *et al*. 2017). GWC (%), VWC (g cm^{-3}), DBD (g cm^{-3}) and P (%) were calculated using Equations 1–4.

$$\mathrm{GWC} = \frac{\mathrm{WS} - \mathrm{DOW}_{105}}{\mathrm{DOW}_{105}} \ \mathrm{x}\, 100 \qquad [1]$$

$$\mathrm{VWC} = \mathrm{DBD}\ \mathrm{x}\ \frac{\mathrm{GWC}}{100} \qquad [2]$$

$$\mathrm{DBD} = \frac{\mathrm{DOW}_{105}}{\mathrm{SV}} \qquad [3]$$

$$\mathrm{P} = 1 - \frac{\mathrm{DBD}}{\mathrm{PD}} \ \mathrm{x}\, 100 \qquad [4]$$

where WS (g) is the wet sample weight, DOW_{105} (g) is the constant weight after drying at 105 °C for 24 hours, and SV (cm^3) is the sample volume.

The peat pH was determined by diluting samples with distilled water at a ratio of 1:5 (w:v) and was measured potentiometrically in combination with a pH electrode. The organic matter content was determined as the loss on ignition (LOI) during combustion of sieved peat samples in a box furnace at 550 °C for five hours. The mass lost during the combustion process represents the organic matter (Rahgozar & Saberian 2015) and was subsequently derived by subtracting the percentage ash content from 100. Total nitrogen (TN) was determined by the Kjeldahl method and total phosphorus (TP) by the spectrophotometric method.

Data analyses

Generalised Linear Models (GLMs) were applied to test for differences in peat physico-chemical properties across the different land use conversion classes (peat swamp forest, grassland and cultivation) and peat depth classes (surface peat: 0–20, 20–40 cm, and deep peat: 40–60, 60–80, 80–100 cm) and their interactions. The GLMs analyses used normal distribution with identity link function or gamma distribution with log link function as the analysis involved continuous data. Post-hoc tests were performed whenever there were significant variations at $p \leq 0.05$, using pairwise comparisons. For all models, the ratio between degrees of freedom (df) and deviance was below 2.5, indicating acceptable model fit. The relationships among peat physico-chemical properties across the different land use conversion classes were examined using regression analyses. Principal Component Analysis (PCA) was also applied, to further evaluate the relationships between peat soil properties and land use conversion. PCA was performed with Z-score transformed data (Z score = $(X_i - X_{avg})/X_{std}$; where X_i is a given value of a variable in a sample, X_{avg} is the average of that variable and X_{std} is its standard deviation). Analyses such as GLMs and regression were carried out in SPSS version 20.0 for Windows, and the PCA was performed using PAST 3.22 (Hammer *et al*. 2001).

RESULTS

Peat thickness and water table depth

The thickness of peat soil differed among land use conversion classes. Peat swamp forest possessed the thickest peat soil deposits ranging from 1.80 to 11.4 m with an average peat depth of 6.63 ± 1.06 m. Grassland had thicker peat deposits (average peat depth 4.01 ± 0.97 m) than cultivation (1.84 ± 0.42 m) areas, which were located at the edges of the peatland and easier to access by communities for cultivation (Figure 2a).

The highest water table level relative to peat surface was found in the peat swamp forest (16.4 ± 3.59 cm), followed by the grassland (14.7 ± 6.23 cm), then the peatland under cultivation management with the lowest water table level (7.00 ± 6.04 cm) (Figure 2b). The positive values of water table level indicate that the water table is above the peat surface.

Peat physical properties

The GWC in both surface and deep peat layers differed significantly between all the land use conversion classes and was highest in peat swamp forest with values of 1765 ± 131 and 1985 ± 97.9 % for surface and deep peat layers, respectively (Table 1, Figure 3a). It is also worth noting that water content was higher in the deeper peat layer. In contrast, VWC for both surface and deep peat layers did not show significant differences between land use conversion classes, as well as between peat layers (Table 1, Figure 3b). Surface peat DBD increased linearly along land use conversion classes and was

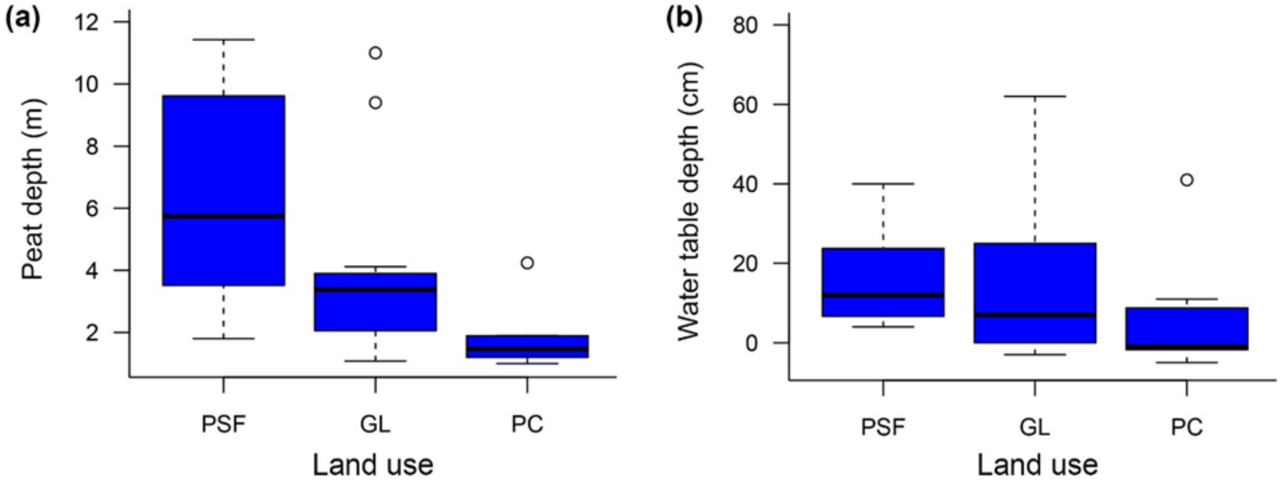

Figure 2. The measured (a) peat depth and (b) water table depth in the peat swamp forest (PSF), grassland (GL) and cultivation (PC) during the sampling period in the study area. The positive and negative values indicate that the water table is above and below the peat surface, respectively.

significantly higher in cultivation (0.28 ± 0.04 g cm^{-3}). In addition, the DBD of deeper peat layers was similar for peat swamp forest and grassland but was significantly higher again in cultivation sites (0.13 ± 0.02 g cm^{-3}) (Table 1, Figure 3c). Peat porosities were high in all the land use conversion classes whereas porosities of surface peat were significantly higher in the peat swamp forest (94.99 ± 0.44 %). Lastly, porosities of deep peat layers were significantly higher in both peat swamp forest (95.62 ± 0.23 %) and grassland (94.84 ± 0.32 %) compared to cultivation (Table 1, Figure 3d).

Peat chemical properties

Peat pH was observed to be significantly higher in both peat swamp forest (5.63 ± 0.05) and grassland (5.51 ± 0.06) compared to cultivation (Table 1, Figure 4a). Peat at both peat swamp forest and grassland had higher OM content with values of 87.6 ± 1.12 and 87.5 ± 1.17 %, respectively, compared to cultivation. Peat OM tended to be higher also in deep layers (85.5 ± 1.32 %) (Table 1, Figure 4b). TN differed significantly between land use conversion classes, being higher in peat swamp forest (1.93 ± 0.03 %) and grassland (1.84 ± 0.05 %) compared to peatland managed as cultivation, and was also higher in surface peat (1.89 ± 0.06 %) (Table 1, Figure 4c). TP was found to be highest at grassland (0.27 ± 0.01 %) and lowest in the peatland used for cultivation (0.17 ± 0.01 %). In contrast to the depth pattern of TN, TP was higher in the deeper peat layer (0.24 ± 0.01 %) (Table 1, Figure 4d).

Table 1. The results of Generalised Linear Models analyses on peat physico-chemical properties. GWC=gravimetric water content, VWC=volumetric water content, DBD=dry bulk density, P=total porosity, OM=organic matter, TN=total nitrogen, TP=total phosphorus

Variable		Wald Chi-square	df	*p* value
GWC	Land use	118	2	<0.001
	Depth	42.5	1	<0.001
	Interaction	15.1	2	0.001
VWC	Land use	2.56	2	0.323
	Depth	0.69	1	0.406
	Interaction	2.60	2	0.272
DBD	Land use	95.5	2	<0.001
	Depth	28.0	1	<0.001
	Interaction	8.38	2	0.015
P	Land use	54.1	2	<0.001
	Depth	19.0	1	<0.001
	Interaction	14.8	2	0.001
pH	Land use	30.3	2	<0.001
	Depth	2.30	1	0.130
	Interaction	4.01	2	0.135
OM	Land use	31.3	2	<0.001
	Depth	9.46	1	0.002
	Interaction	3.78	2	0.151
TN	Land use	38.8	2	<0.001
	Depth	4.71	1	0.030
	Interaction	1.30	2	0.522
TP	Land use	41.9	2	<0.001
	Depth	5.71	1	0.017
	Interaction	2.49	2	0.288

Interrelationships between peat properties and land use

The regression analyses showed a significant relationship between physical and chemical properties of peat. GWC showed a positive S-curve relationship with OM, TN and TP (Figures 5a, b and c). On the other hand, DBD had a negative exponential relationship with OM, TN and TP content in peat (Figures 5d, e and f).

The relationships between peat physico-chemical properties and land use conversion classes are depicted in the PCA biplot (Figure 6) with two principal components explaining 69.53 % of the total variability. The first principal component accounted for 56.27 % of the total variability with higher positive loadings for GWC (r=0.38), P (r=0.43), OM (r=0.43), TN(r=0.34), TP (r=0.33) and negative loading for DBD (r=-0.56). As reflected in the PCA biplot, all of the peat physico-chemical properties associated with the first principal component increased towards forest and grassland sites, except for DBD which increased towards peatland under cultivation management. Furthermore, the second principal component accounted for 13.26 % of the total variability with high positive loading for VWC (r=0.93) and as well pH (r=0.29), and these peat properties are also likely to be associated with peat swamp forest and grassland.

DISCUSSION

Changes in peat physical properties

The present investigation revealed that land use conversion resulted in significant reduction in peat water content. For example, greater reduction in peat GWC was observed for surface peat where conversion of peat swamp forest to grassland and cultivation resulted in loss of water content

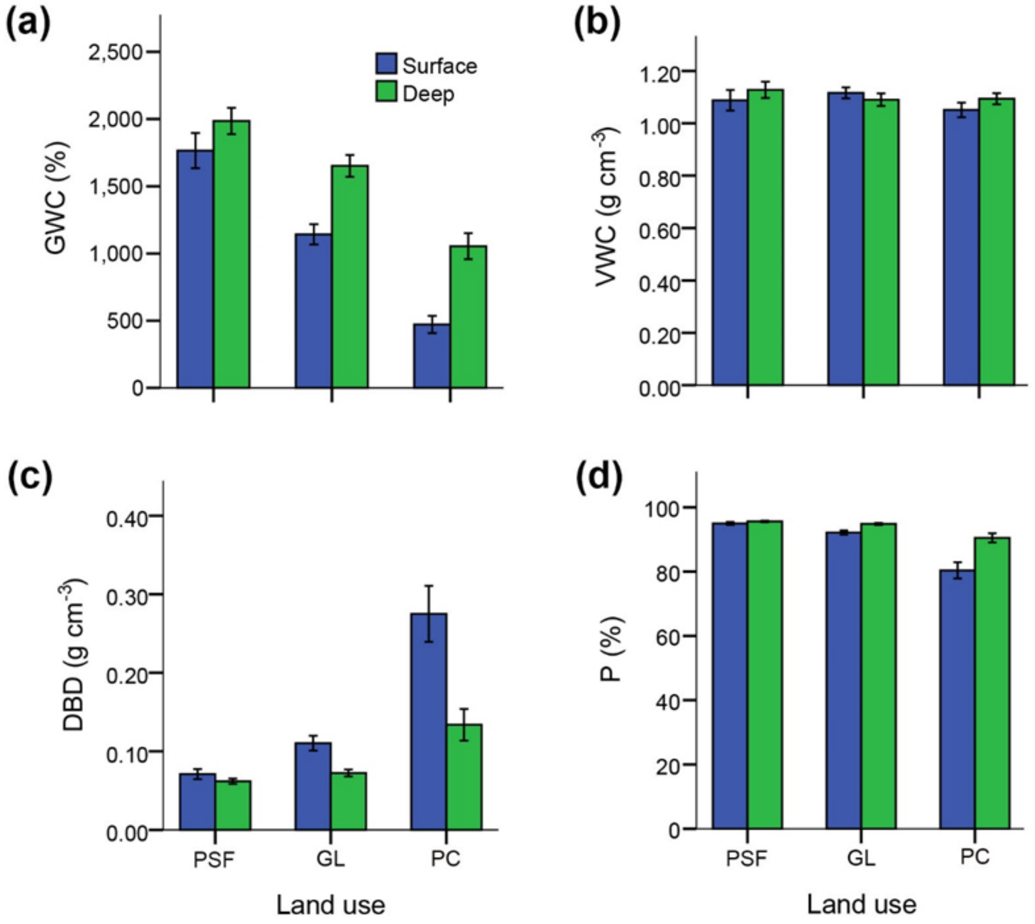

Figure 3. The difference in (a) gravimetric water content (GWC), (b) volumetric water content (VWC), (c) dry bulk density (DBD) and (d) total porosity (P) of peat soils in the different land use conversion classes in the study area. Average values for land conversion classes and standard error bars are shown. PSF=peat swamp forest, GL=grassland, PC=cultivation, surface peat layers (0–20, 20–40 cm), deep peat layers (40–60, 60–80, 80–100 cm).

amounting to about 35.3 and 73.3 %, respectively. In this study the observed water contents in all peat layers in peat swamp forest areas were higher than the reported average value for the tropical peatland forest of North Selangor Peat Swamp Forest (NSPSF) in Malaysia (627 ± 90 %; Tonks *et al*. 2017). The reduction in peat water content is the direct consequence of peat drainage and conversion of peatland forest into other land uses, particularly agriculture (Anshari *et al*. 2010, Hooijer *et al*. 2012), which is also reflected in the decreasing water table depth from peat swamp forest to cultivation in the study area (Figure 2b). Apparently, the surface peat showed greater reduction in water content and was often subjected to changes in water table position which was likely to have increased oxygen availability and subsequently enhanced peat decomposition (Jauhiainen *et al*. 2012, Lampela *et al*. 2014).

The conversion of peatland forest altered the peat physical properties as reflected by peat bulk density in cultivation sites that was four times higher than in peat swamp forest. Similarly, other studies have reported increased peat bulk density when tropical peat swamp forests are converted to oil or sago palm plantations (Miyamoto *et al*. 2009, Anshari *et al*. 2010) and agriculture (Könönen *et al*. 2015). It is also important to note that the recorded peat bulk density in peat swamp forest areas of this study were comparable to tropical peatland forests of SE Asia, ranging from 0.07–0.15 g cm^{-3} (Anshari *et al*. 2010, Lampela *et al*. 2014, Könönen *et al*. 2015, Tonks *et al*. 2017). The higher peat bulk density in the cultivation sites can be attributed to the mixing of mineral soils with peat (Murdiyarso *et al*. 2009) due to cultivation and probably surface erosion in the margins of the peatland. Additionally, higher peat bulk densities in cultivated areas are the consequence of compaction arising from heavy machinery applying pressure to the peat and shrinkage that occurs through contraction of organic fibres upon

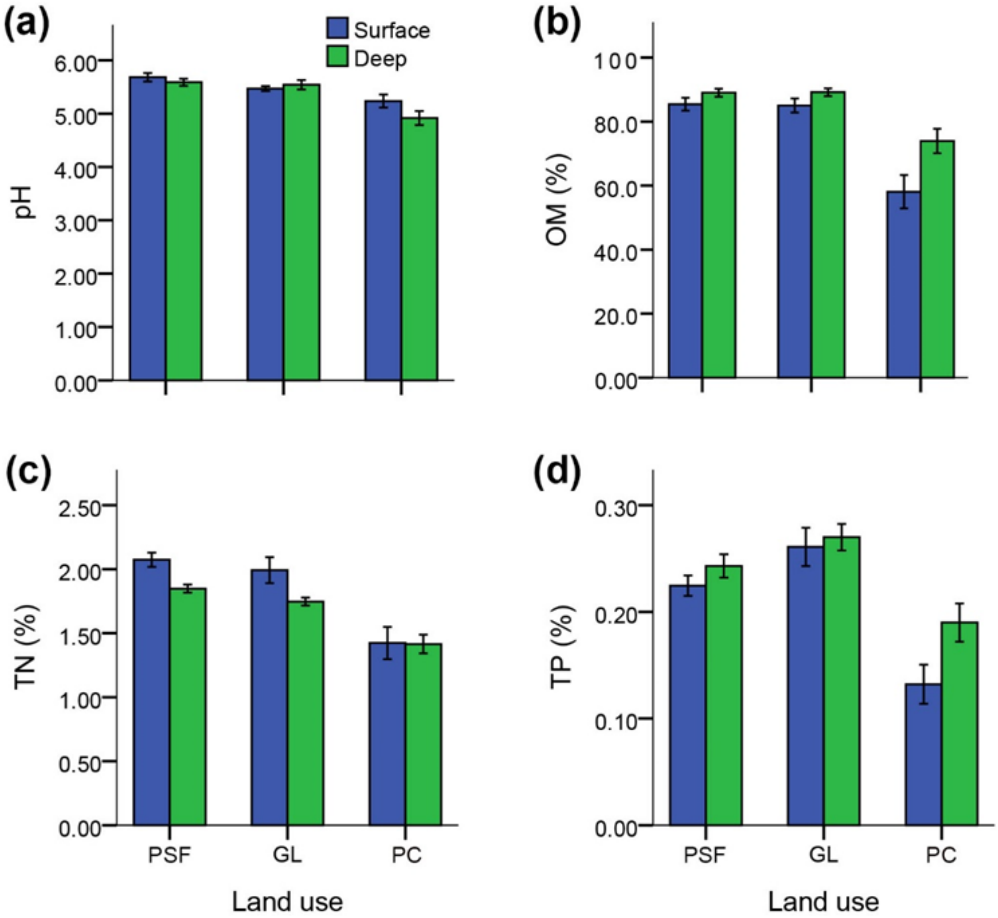

Figure 4. The difference in (a) pH, (b) organic matter (OM), (c) total nitrogen (TN) and (d) total phosphorus (TP) of peat soils in the different land use conversion classes in the study area. Average values for land conversion classes and standard error bars are shown. PSF=peat swamp forest, GL=grassland, PC=cultivation, surface peat layers (0–20, 20–40 cm), deep peat layers (40–60, 60–80, 80–100 cm).

drying, along with the breakdown of organic compounds (Hooijer *et al*. 2012). It has been noted that higher bulk densities in cultivated and converted peatland forest further indicate peat soil degradation (Guillaume *et al*. 2016).

Furthermore, the porosity of the surface peat layers in the peat swamp forest was comparable to peat porosities reported in tropical peatland forest in Central Kalimantan, Indonesia (89.20 ± 1.60 to 90.90 ± 0.60 %; Könönen *et al*. 2015) and NSPSF, Malaysia (95.20 ± 0.40 %; Tonks *et al*. 2017). It was observed that peat porosities decreased with land use conversion, with lower values in peatland under cultivation management. Apart from the possible effect of compaction from agrotechnical treatments, low porosities in peatland with cultivation are an indication of peat decomposition which decreases the proportion of large pores by breaking down plant debris into smaller fragments (Rezanezhad *et al*. 2016), consequently reducing the water-holding capacity of peat soil.

Changes in peat chemical properties

The recorded peat pH values in this study were slightly higher than the values reported for tropical peatlands by some authors (3.4 ± 0.06 to 3.9 ± 0.08 by Tonks *et al*. 2017; 3.53–3.77 by Aribal & Fernando 2018) but similar to the values (5.40–6.40) reported by Anamulai *et al*. (2019). The peat was found to be less acidic in peat swamp forest and grassland compared to cultivation sites. This finding of our study does not mirror the results of earlier studies which indicated higher pH in cultivation or intensively managed peat (Könönen *et al*. 2015, Tonks *et al*. 2017, Bader *et al*. 2018). It has been noted that an increase of pH in cultivated peat soil has been associated with the application of fertiliser (Anshari *et al*. 2010). The fertilisers that are most commonly applied in the cultivation of tropical peatlands are urea and ammonium sulphate, which can increase the rate of mineralisation and nitrification in peat soil leading to an eventual rise in pH (Ariffin *et al*. 2015). In addition, applications of

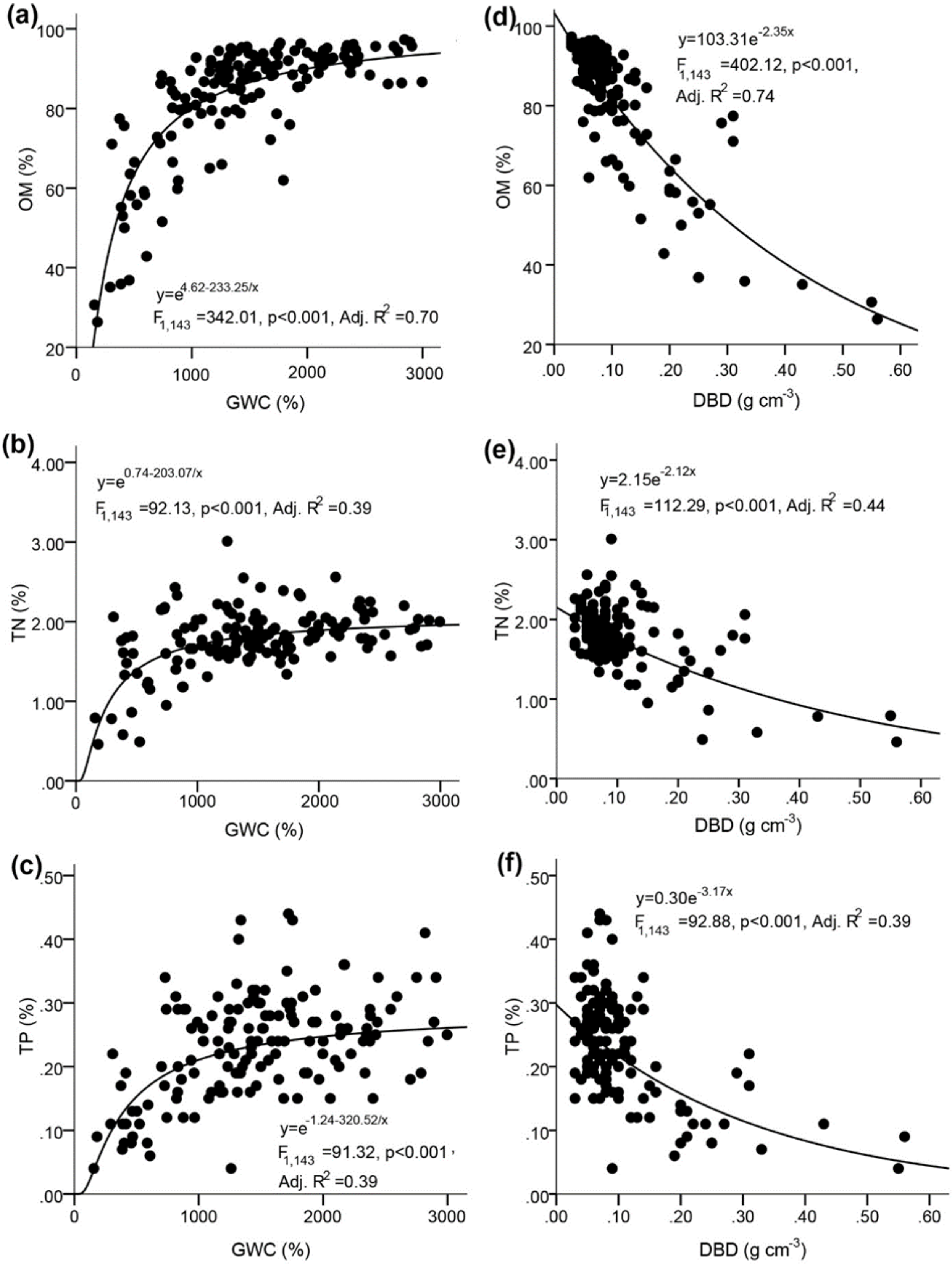

Figure 5. The relationships between (a) gravimetric water content (GWC) and organic matter (OM), (b) gravimetric water content (GWC) and total nitrogen (TN), (c) gravimetric water content (GWC) and total phosphorus (TP), (d) dry bulk density (DBD) and organic matter (OM), (e) dry bulk density (DBD) and total nitrogen (TN), (f) dry bulk density (DBD) and total phosphorus (TP). The significant regression lines and their equations, R^2, F and p-values are presented.

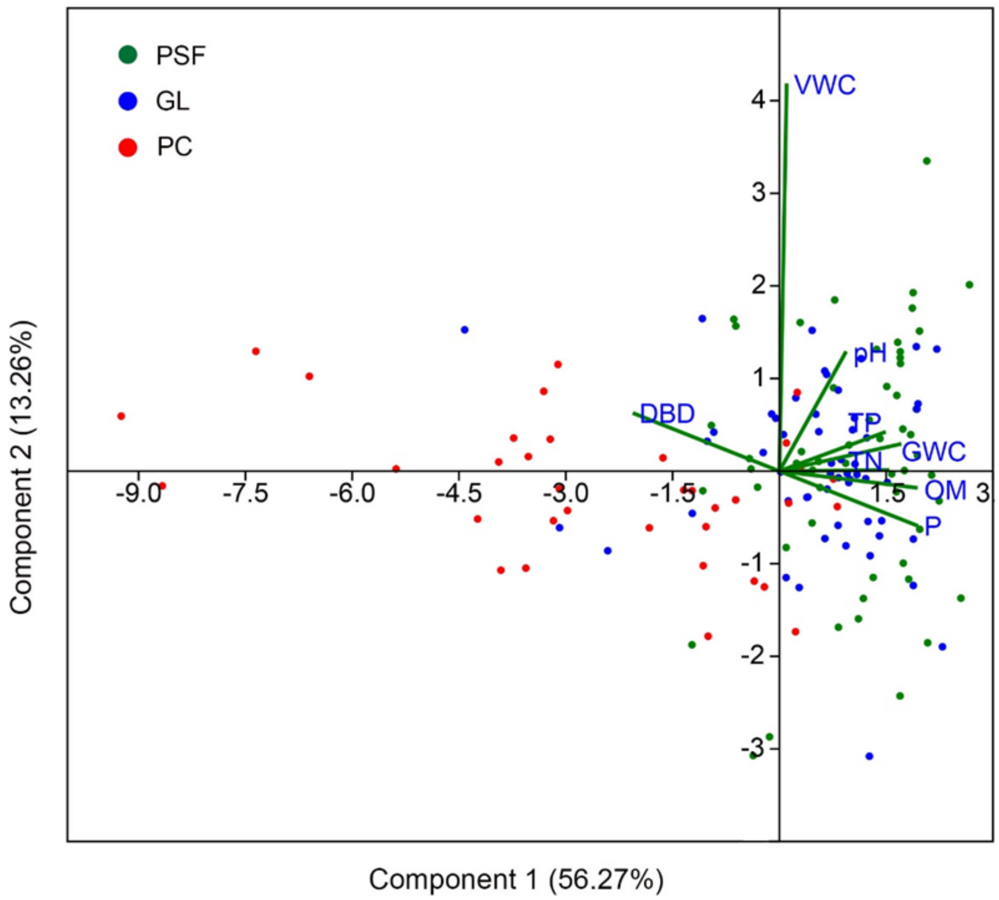

Figure 6. Principal Component Analysis (PCA) biplot showing the relationships between peat soil physicochemical properties and land use conversion classes. PSF=peat swamp forest, GL=grassland, PC=cultivation, GWC=gravimetric water content, VWC=volumetric water content, DBD=dry bulk density, P=total porosity, OM=organic matter, TN=total nitrogen, TP=total phosphorus.

fertilisers coupled with soil conditioners or amendments such as hydrated minerals and plant derived ash have liming effects on peat soil (Choo *et al*. 2020). But in the study area, cultivation sites (particularly rice fields) had lower pH, which may explain their lower productivity compared to rice field areas on mineral soils.

The observed OM content in the peat swamp forest was comparable to that in NSPSF Malaysia, as reported by Tonks *et al*. (2017), with a value of 94.1 ± 1.50 %; but slightly higher than in Caimpugan peat swamp forest on Mindanao Island in the Philippines (65.7–73.7 %; Aribal & Fernando 2018). OM content in the cultivated peatland was lower than in the peat swamp forest which provides evidence that conversion of peatland forest results in peat decomposition (Tonks *et al*. 2017). Specifically, such loss in OM content is the consequence of enhanced microbial respiration and peat oxidation, mineralisation, and loss of the surrounding organic matrix, as well as the application of fertilisers (Grønlund *et al*. 2008, Anshari *et al*. 2010, Tonks *et al*. 2017, Leifeld *et al*. 2020). It is also important to note that the comparison of organic matter content between grassland and peat swamp forest in LSBP suggests that abandonment of cultivated peatlands may prevent complete degradation of the peat. When cultivated peatlands are abandoned, ditches and canals become re-vegetated which might slow down the process of draining, as observed in the study area.

The TN values recorded in the peat swamp forests were comparable with the results of studies conducted in tropical peatlands in Kalimantan, Indonesia by Lampela *et al*. (2014), where the average nitrogen content was 1.60 %. Anshari *et al*. (2010) found that average nitrogen content was 1.57 % for coastal peat forest, and Könönen *et al*. (2015) found an average of 0.86 to 1.60 % for undrained peat forest sites. TN linearly decreased from peat swamp forest through cultivated peatland indicating that land use conversion results in peat degradation. Under prolonged drained conditions, the nitrogen losses through mineralisation result in N_2O emissions from peatlands (Jauhiainen *et al*. 2012). At a later stage, loss of nitrogen from peatland due to drainage is indicated by an increase in concentrations of nitrogen forms (i.e., ammonium, nitrate and dissolved organic nitrogen) in the soil solution (Frank *et al*. 2014). However, nitrogen concentrations in peat at agricultural sites may be maintained or increased by the addition of fertilisers (Krüger *et al*. 2015). It is also important to note that the higher nitrogen content in the surface peat layers is explained by the deposition of litter, while the lower nitrogen content in deeper layers is due to the advanced decomposition of peat (Könönen *et al*. 2015).

Land use conversion also significantly reduces mineral nutrients in peat as shown by the lower phosphorus in the cultivation than in grassland and peat swamp forest. A similar pattern was observed when tropical peatland forests were converted to smallholder cropping (Könönen *et al*. 2015) and sago palm plantation (Miyamoto *et al*. 2009). The lower nutrient concentrations in terms of e.g. phosphorus in the cultivated peatland means that these areas offer a nutrient impoverished substrate for plants compared to peat swamp forests (Könönen *et al*. 2015). Although the addition of fertiliser may maintain relatively higher concentration of nutrients in cultivated peat (Miyamoto *et al*. 2009), this may result in enhanced decomposition and lead to increased rates of peat loss and greenhouse gas emissions (Jauhiainen *et al*. 2014).

Interrelationships between peat physico-chemical properties

This study revealed a strong direct relationship between water content and organic matter, indicating that the reduction in peat water content results in organic matter loss (Figure 5a). Such a relationship was observed also in the study of Tonks *et al*. (2017) in a tropical peatland. Land use conversion in tropical peatlands involves clearing of vegetation and drainage which eventually reduces the water content of peat (Hooijer *et al*. 2012, Grzywna 2017). In this study, it was observed that peat water content decreased from peat swamp forest through cultivation, which was likewise reflected by a decreasing trend in water table depth. Under low water table level and water content, peat materials are exposed to air which eventually accelerates peat decomposition and organic matter loss (Anshari *et al*. 2010). Similarly, there was a positive relationship between water content and nutrients such as total nitrogen and total phosphorus (Figures 5b and c) which may indicate that the reduction in peat water content also leads to loss of the said nutrients. Reduction in peat water content primarily from drainage ultimately results in the loss of nutrients through peat decomposition and mineralisation (Jauhiainen *et al*. 2012). For example, Frank *et al*. (2014) found a strong association between drainage and nutrients in soil water where drained peatland has high concentrations of dissolved nitrogen as a result of increased mineralisation, which can be lost or leach to downstream water bodies. In addition, draining of peat contributes to the depletion of more soluble elements such as phosphorus (Könönen *et al*. 2015, Negassa *et al*. 2020). Accordingly, in this study, lower total nitrogen and total phosphorus were observed in the cultivated peatland where the peat had lower moisture level and was subjected to intensive draining.

Furthermore, bulk density is an indicator of peatland degradation (Anshari *et al*. 2010, Guillaume *et al*. 2016) where peat bulk density was found to be strongly negatively correlated with organic matter (Figure 5d). Such an increase in peat bulk density may result from particulate organic matter being flushed out of surface peat and becoming concentrated close to the water table (Moore *et al*. 2013), together with compaction as a consequence of aerobic decomposition of peat (Könönen *et al*. 2015). In this study it was found that the cultivation areas had higher peat bulk densities with lower organic matter contents (Figure 6). Furthermore, a negative association was found between bulk density and nutrient content in soil where the increase in peat bulk density was accompanied by a decrease in nutrients. The increase in peat bulk density also suggests an increase in mineralisation under drained conditions, which releases more nutrients (Frank *et al*. 2014). However, in some instances, mineral nutrients in cultivated and compacted peat are retained when there are regular and heavy inputs of fertilisers (Anshari *et al*. 2010).

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AUTHOR CONTRIBUTIONS

SCPD, AOA and SV-P designed the study. All authors performed data collection and analyses, and contributed significantly to development of the manuscript. The initial draft of the manuscript was prepared by SCPD and AOA, and the rest of the authors commented on it. All authors contributed to revisions and approved the final version.

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